CST MWS simulation of the SARAF RFQ 1.5 MeV/nucleon proton/deuteron accelerator

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Outline

1. SARAF accelerator
2. Presentation of the four rods RFQ
3. CST MWS simulation of RFQ
4. Comparison to the RFQ conditioning measurements and findings
5. Concluded RFQ modifications
SARAF – Soreq Applied Research Accelerator Facility

RF Superconducting Linear Accelerator

Target Hall

Phase I 2010

LEBT
RFQ
PSM
MEBT
EIS

Energy: 20 keV/u
1.5 MeV/u
p: 4 MeV
d: 5.2 MeV
L (m): 5 9 12

5 x SC Modules

Phase II 2014

40 MeV
31

Thermal n radiography
n Diffraction
Beam Dump
Nuclear Astrophysics
Radioactive beams
Radio Pharmaceuticals

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A. Nagler et al., LINAC 2006
176 MHz Radio Frequency Quadrupole

- In factory 2005
- On site 2006
- P. Fischer
  EPAC 2006
The four rods RFQ function

- The RFQ get a 20 kev/nucleon 4 mA dc charged beam:
- The first step is to converge the beam envelope diameter to few mm at the radial matcher
- The second step is to bunch the charged particles along the beam axis to few mm while the distance between the bunches is 10 mm
- The third step is gently to accelerate the beam up to 1.5 MeV/nucleon
The four rods RFQ fundamental structure

- The RFQ consist of two pairs of RF electrodes with supported by 40 stems standing on a common base plate.
- The odd stems support one pair and the even stems support the second pair with a negative polarity.
- The 40 stems subdivide the RFQ resonator to 39 RF cells. The stems and the base plate generate the inductance coils and the electrodes serve as capacitors.
- The four electrodes generate an RF quadruple that is used to transversely converge the beam.
- The electrodes modulation along the RFQ is used to bunch and to accelerate the beam.

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The SARAF four rods RFQ

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The RFQ CST MWS simulation

• The coupler coil, connected to a coaxial line, is applied to transfer the RF power

• The tuning plates are used to tune the 39 RF cells, and the two plungers are used for real time matching of the RFQ to the supplied RF 250 kW, 176 MHz.

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The RFQ includes 39 RF cells
The RF cell surface current

Type: Surface Current (peak)
Monitor: Node 1
Maximum 3D: 41702.5 A/n at 22.4232 / 5.02047 / -86.1718
Frequency: 174.039
Loaded Freq: 174.032
External Q: 2971.76
Phase: 90 degrees

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The magnetic field at the RF cell

<table>
<thead>
<tr>
<th>Type</th>
<th>H-Field (peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitor</td>
<td>Node 1</td>
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<tr>
<td>Plane at 2</td>
<td>-2146.52</td>
</tr>
<tr>
<td>Maximum-2D</td>
<td>13737.2 A/m at 17.6617 / -19.0621 / -2146.52</td>
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<tr>
<td>Frequency</td>
<td>174.039</td>
</tr>
<tr>
<td>Phase</td>
<td>90 degrees</td>
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</table>

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The electrodes RF quadruple fields

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The RFQ coupler coil
The coupler induced H field

<table>
<thead>
<tr>
<th>Type</th>
<th>H-Field (peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>45226.3 μA/m at 22.5 GHz / -86.29 mV</td>
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<tr>
<td>Frequency</td>
<td>174.039 GHz</td>
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<tr>
<td>Loaded Freq</td>
<td>174.832 GHz</td>
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<tr>
<td>External Q</td>
<td>2971.76</td>
</tr>
<tr>
<td>Phase</td>
<td>90 degrees</td>
</tr>
</tbody>
</table>

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The RFQ coupler port
The RFQ coupler

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The simulated coupler

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Simulation of the RFQ including the coupler port

• The RFQ Qe and the RFQ fields could be found by the following steps:

  1. The input RF coaxial line impedance ≈ 50 ohm
     \[ Z = \frac{V}{I} = \ln \left( \frac{R_{\text{ext}}}{R_{\text{in}}} \right) \left( \frac{\mu}{\varepsilon} \right)^{0.5} / (2\pi) \]
  2. At matching conditions:
     \[ Q_e = Q_0 = \frac{U}{P/\omega} \]

Where:

  Q- quality factor
  U- the simulated internal stored energy
  P- the simulated supplied/dissipated power
The RFQ simulation fields at normal conditions – Pascal Balleyguier CEA/DPTA

\[ Q_{ext_{1,2}} = \frac{\omega \iiint_{cavity} |F|_{1,2}^2 \, dV}{c \iint_{coaxiallinecrosssection} |F_{1,2}|^2 \, ds} \]

\[ Q_{ext_1} \quad \text{for} \quad H = 0 \quad \text{at line cross section} \]

\[ Q_{ext_2} \quad \text{for} \quad E = 0 \quad \text{at line cross section} \]

\[ Q_{ext} = Q_{ext_1} + Q_{ext_2} \]

Combining the two standing waves in quadruple phase gives the fields within normal operating condition after normalization to the same energy density at the line cross section

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CST MWS simulation of Qext

- The RFQ Qext was calculated with the CST MWS eigenmode solver—once by following P. Balleyguier method and once by defining an external port at the coaxial line cross section.
- Both methods gave similar Qext around 3000 while the measured Qext is 3600.
- These results are in reasonable agreement since by variation of the coupler loop distance from the stems by few mm one can achieve the desired matching.
Coupler loop mesh for CST MWS

- The loop could be simulate without shorts by high mesh resolution

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Tuning the simulated field flatness along the RFQ to match the realistic fields

- The simulated field flatness along the RFQ was achieved by variation of the 13 tuning plates heights along the 39 RF cells by 3mm each.
- The next effort will be to apply more homogenous mesh.

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Simulation of the fields at bottom electrodes

The local cutting at the bottom electrodes reduced the parasitic fields towards the stems with the negative polarity.

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The fields between the electrodes vs. the parasitic fields

After local cutting the parasitic fields at electrodes bottom are smaller than the inner electrodes fields used to converge and bunch the beam.

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The maximum measured external tank surface temperature around 50°C was measured at the bottom of the coupler port. The cooling line will be extended to the port bottom.

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Ansys thermal analysis of the coupler port

The thermal contact between the port and the tank is through the welding only.

The geometry model (Inventor)
Ansys thermal simulation - Convection input
CST simulation results were inserted as boundary conditions (heat load) to ANSYS.

30 °C boundary condition at Bottom Base plate.
External surfaces temperature
Without the cooling plate –

Max surface temp. - 50.5 °C
Port and tank temperature – Without the cooling plate

Max temp. - 126.6 °C
Port and tank temperature – Internal view without the cooling plate

Max temp.: 126.6 °C
Port and tank temperature – with the cooling plate

Max temp. - 118 °C
Port and tank temperature – Internal view with the cooling plate

The cooling plate reduced the Max. temp. by less than 10 °C
Port and tank temperature – Internal view
with the cooling plate

Full contact between the port and the tank

Max temp. - 81 °C

Significant max. temp. reduction achieved due to the full contact between the port and the tank
Port and tank temperature – External view with the cooling plate

Full contact between the port and the tank can be achieved by thermal conducting interface material.
Surface field around the plunger

The CST simulated heat load is in good agreement with the melting plunger cup

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A modified solid plunger enable better cooling of the plunger and a thicker conducting contact between the tuning plate and the stems prevents the melting of the tuning plates contacts.

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Surface field on the end flange

Cooling lines at the end flanges were applied to remove the surface current heat load

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Summary

• RFQ was simulated including the rods modulation and the coupler

• RFQ fields and surface current on the plunger, bottom rods, coupler port and end flange pattern are in good agreement with the RFQ findings during RFQ conditioning

• The re-evaluation of the RFQ thermo hydraulic analysis will be based on the RFQ CST simulation